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Abstract

Non-native, invasive plants are projected to shift their ranges with climate change, creating hotspots of risk where a multitude of novel species may soon establish and spread. The Northeast U.S. is one such hotspot. However, because monitoring for novel species is costly, these range-shifting invasive plants need to be prioritized. Preventing negative impacts is a key goal of management, thus, comparing the potential impacts of range-shifting invasive species could inform this prioritization. Here, we adapted the Environmental Impacts Classification for Alien Taxa (EICAT) protocol to evaluate potential impacts of 100 invasive plants that could establish either currently or by 2050 in the states of New York, Massachusetts, Connecticut, or Rhode Island. We searched Web of Science for each species and identified papers reporting ecological, economic, human health, or agricultural impacts. We scored ecological impacts from 1 ('minimal concern') to 4 ('major') and socio-ecological impacts as present or absent. We evaluated 865 impact studies and categorized 20 species as high-impact, 36 as medium-impact, and 26 as low-impact. We further refined high-impact invasive species based on whether major impacts affect ecosystems found in Northeast U.S. and identified five high-priority species: *Anthriscus caucalis*, *Arundo donax*, *Avena barbata*, *Ludwigia grandiflora*, and *Rubus ulmifolius.* Additional research is needed for 18 data-deficient species, which had no studies reporting impacts. Identifying and prioritizing range-shifting invasive plants provides a unique opportunity for early detection and rapid response that targets future problem species before they can establish and spread. This research illustrates the feasibility of using impacts assessments on range-shifting invasive species in order to inform proactive policy and management.

Keywords: Climate change; EICAT; impact; invasion risk; range-shift

Introduction

Non-native, invasive species are a well-known driver of global change, causing both economic and ecological impacts (Mack et al. 2000; Pimentel et al. 2005). With climate change, invasive plants are projected to shift their ranges, creating a new pool of potentially high-impact species in many regions (Bradley et al. 2010; O'Donnell et al. 2012; Gallagher et al. 2013; Bellard et al. 2013; Allen and Bradley 2016). However, with limited management resources, it is impossible to monitor for and respond to all range-shifting invasive plants. A primary motivation for managing invasive species is to reduce their impacts (Parker et al. 1999), thus, identifying range-shifting invasive plants that have the highest potential impacts can support proactive monitoring and management.

Range-shifting species include both native and non-natives (Essl et al. 2019). Although some native range-shifting species will have negative impacts (Mueller and Hellmann 2008; Wallingford et al. 2019), here we focus only on those identified as non-native and invasive. That is, species non-native (here, non-native to the U.S.), spreading over a considerable area (Richardson et al. 2000), and likely to cause economic or environmental harm (Executive Order 13112 1999). Climate change is projected to increase risk from these invasive species in several regions, including Northeastern North America (Bellard et al. 2013; Allen and Bradley 2016). Thus, negative impacts caused by these invasive species in more southerly states could expand to affect the Northeast U.S. with climate change. Based on their spatial analyses, Allen and Bradley (2017) created watch lists of invasive plant species with no spatial occurrence data in a given state or region, but with the potential to establish there either currently or by mid-century with climate change. For the Northeast U.S. region (New York and southern New England states) the watch list included 100 range-shifting invasive plants.

Range-shifting invasive species are a concern because of their potential impacts. Invasive plants negatively affect native species and ecosystems in a variety of ways, reducing native species abundance and diversity and altering ecosystem function (Ehrenfeld and Scott 2001; Vilà et al. 2011; Bradley et al. 2019). In addition to ecological impacts, invasive plants contribute to an estimated $24 billion in crop losses and $3 billion in control costs annually in the U.S. (Pimentel et al. 2005), can reduce crop yields by 30-50% (Zimdahl 2007), and reduce the quality of forage for livestock (Finnoff et al. 2008). Overall, the negative ecological and socio-economic consequences of invasive plants underscore the benefits of proactively identifying and preventing high-impact species from gaining a foothold in the Northeast U.S.

Identifying new invasive plant populations through early detection and rapid response (EDRR; Westbrooks 2004) can be effective for preventing a widespread invasion (Moody and Mack 1988). By the time a species has become widespread, eradication is nearly impossible (Rejmánek and Pitcairn 2002; Rejmánek et al. 2005), and only containment and impact reduction options remain (Panetta 2012). Therefore, detection and prevention of invasive plants before they become widely established is cost-effective and vital for stopping harmful invasions. For range-shifting invasive species, EDRR targets the leading edge of an invasion, removing populations that could seed future spread (Moody and Mack 1988; Westbrooks 2004). But knowing which species to look for is a critical component of effective EDRR.

Identifying range-shifting invasive species was the highest priority need for climate adaptation reported by U.S. natural resource managers (Ernest Johnson 2018). However, with hundreds of potential target invasive species (Allen and Bradley 2016), risk assessment and prioritization is critical for practical monitoring and EDRR programs. A variety of risk assessments currently exist for assessing likelihood of plant invasiveness (e.g., weed risk assessments; Pheloung et al. 1999; Koop et al. 2012; Conser et al. 2015; Booy et al. 2017). However, these assessments focus on identifying potentially invasive plants from a pool of novel plants. With range-shifting invasive species, the pool of plants is already known. Thus, a risk assessment that focuses on their potential to have negative impacts is appropriate.

The Environmental Impact Classification of Alien Taxa (EICAT) assesses the magnitude of invasive species' impacts using the scientific literature (Blackburn et al. 2014). This protocol was developed in consultation with the International Union for Conservation of Nature (IUCN) and was formally adopted as their method for classifying the environmental impact of alien species. The overall aim of EICAT is to quantify the magnitude of known impacts from all available studies such that potential impacts can be consistently compared between invasive species (Blackburn et al. 2014; Hawkins et al. 2015). This approach has previously been used to evaluate the relative impacts of invasive birds, amphibians, mammals, and molluscs (Evans et al. 2016; Kumschick et al. 2017; Hagen and Kumschick 2018; Kesner and Kumschick 2018). EICAT has also been used to compare impacts of bamboo species (Canavan et al. 2019). Thus, EICAT provides a consistent, repeatable framework for assessing and comparing the potential impacts of invasive species.

Here, we used EICAT to assess the potential impacts of 100 invasive plants that are projected to expand their ranges into the states of New York and Massachusetts, Connecticut, and Rhode Island (southern New England) either currently or by mid-century with climate change. We assessed the magnitude of impact on ecosystems as well as the presence of impacts on socio-economic systems to identify high-priority species for monitoring and preventative policy. This type of prioritization provides a cost-effective, proactive strategy to prevent the spread of invasions facilitated by climate change.

Methods

Target species

We used a watch list of 100 invasive plant species (**Table S1**) that could establish in the states of New York, Connecticut, Massachusetts, or Rhode Island, either currently or by 2050 with climate change (Allen and Bradley 2017). This list was based on Allen and Bradley (2016), who modeled current and future potential ranges for nearly 900 invasive plant species within the continental U.S. Each of the target species has been identified as a non-native 'noxious weed' by state and/or federal policymakers or identified as a non-native invasive plant by the Invasive Plant Atlas of the US (https://www.invasiveplantatlas.org/). The 100 range-shifting invasive plants are predominantly non-native to North America, although three species are native to Canada.

The spatial models were based on occurrence data from herbaria and management records (Allen and Bradley 2016) and the resulting list included only species that had not been reported in the region by these spatial datasets. However, some of the watch list species may be present in part of the region but not reported to spatial databases used by Allen and Bradley (2016), or may have expanded subsequent to the 2016 analyses. Therefore, we also used the USDA Plants database (https://plants.sc.egov.usda.gov/) to assess presence and proximity of high-impact species to the Northeast.

Literature search

In order to assess the relative impacts of the 100 target species, we modified the Environmental Impacts Classification for Alien Taxa (EICAT) protocol (Hawkins et al. 2015). A primary goal of EICAT is to develop a consistent method of leveraging the peer-reviewed literature to categorize the magnitude of environmental impacts of invasive species. This approach begins with a title and abstract search of the literature to identify any papers reporting impacts for the target species. For each species, we used the Integrated Taxonomic Information System (ITIS) to identify any synonyms or previous taxonomies. We then used the Web of Science Core Collection to search for papers using the genus and species of the target plant as well as any synonyms identified in ITIS (e.g., *Aegilops ovata* OR *Aegilops geniculata*). Each of the titles and abstracts of all returned papers was scanned for evidence of an impact study. We looked in titles and abstract for keywords such as "impact", "effect", "influence", "affect", "correlate", or "cause" as well as references to the species as invasive or references to an impact mechanism (e.g., competition or crop loss; see below). Because the impacts assessments were focused on the potential for negative impacts associated with invasive plants, papers reporting positive impacts (e.g., papers describing the species as a potential dietary supplement or biofuel) were not included. Literature searches were conducted between June-December 2018.

Data collection

All papers reporting an environmental, economic, agricultural, or human health impact of a target species (Table S1) were compiled. Impacts information was recorded to follow the EICAT protocol (Hawkins et al. 2015) with some modifications described below and also outlined in Table S2. Following Hawkins et al. (2015), we recorded the species information (scientific name, common name, growth form, USDA code) and citation information (first author, year, journal, DOI, citation).

We expanded the EICAT protocol to include socio-economic impacts in addition to ecological impacts. We recorded this under a column called ‘Affected System’. Affected

Systems are defined as: 1) **Ecological** – the alien taxon has impacts which affect native species or communities. 2) **Human Health** – the alien taxon has impacts which affect human health independently of crop systems (e.g. allergies). 3) **Economic** – the alien taxon has impacts which affect infrastructure or economics independent of crop systems (e.g. road deterioration). 4) **Agricultural** – the alien taxon affects plant or animal agriculture (e.g. crop loss). Although socio-economic impact magnitudes have been proposed (SEICAT; Bacher et al. 2018), they focus on change or abandonment of an activity (e.g. agricultural abandonment). The socio-economic papers reviewed here were predominantly related to crop losses, but did not describe any change in agricultural activity. As a result, the papers reviewed here did not fit well within the SEICAT framework (Bacher et al. 2018) and were instead recorded as 'present'.

Reported ecological impacts were classified into one or more of the following 9 impact mechanisms that are relevant for plants (Hawkins et al. 2015): 1) **Competition** – the alien taxon competes with native taxa for resources (e.g. food, water, space). 2) **Hybridization** – the alien taxon hybridizes with native taxa. 3) **Disease transmission** – the alien taxon transmits diseases to native taxa. 4) **Poisoning/toxicity** – the alien taxon is toxic, or allergenic by ingestion, inhalation or contact to wildlife, allelopathic to plants, or alters microbial communities. 5) **Bio-fouling** – the accumulation of individuals of the alien taxon on wetted surfaces. 6) **Chemical impact** – the alien taxon causes changes to the chemical characteristics of the ecosystem, including altered soil or water nutrients. 7) **Physical impact** – the alien taxon causes changes to the physical characteristics of the ecosystem, including altered fire regimes, water cycling or soil erosion. 8) **Structural impact** – the alien taxon causes changes to the structural characteristics of the ecosystem, such as adding or removing canopy levels, altering structural resources (e.g., nesting habitat), trapping species at higher trophic levels (e.g., bees stuck in flowers). 9)

Interaction – The alien taxon facilitates other alien taxa, (e.g., through habitat modification, addition of resources).

For each study reporting ecological impacts, impact magnitude was scored on a 1-4 scale: **1 = Minimal Concern** is defined as discernible impacts, but no effects on individual fitness of native species. **2 = Minor** is defined as fitness of individuals reduced, but no impact on populations. **3 = Moderate** is defined as changes to populations, but not to community composition. **4 = Major** is defined as changes to the native community composition. Here, we interpreted a change in community composition as a decline in community richness, diversity, evenness, or overall native species abundance. For some ecological impact mechanisms, particularly chemical and physical alterations, effects on native species were often not reported. When it seemed likely based on the paper that native communities would be affected (e.g., altered hydrology caused by the invasive negatively affects native riparian communities), we scored the impact as major. When it was unclear from the paper whether native species would be affected (e.g., the invasive species decreases carbon storage), we scored the impact as minimal concern.

In addition to the data described above, the following details about each paper were also included in the database: country where the study took place, invaded habitat (based on the IUCN Habitat(s) Classification Scheme), maximum extent of the study, plot size, number of plots, whether the site was managed or not, and the taxon of the affected species or community. This information will enable end users to make a more nuanced judgment of threats to specific ecosystems or sectors. For example, invaded habitat provides information about the types of ecosystems where impacts have been reported and can be used by natural resource managers to infer whether the ecosystems that they manage are at risk. An outline of all modifications to the EICAT protocol is presented in Table S2.

We assigned each species into High, Medium, and Low Priority categories. **High-priority species** were those with a maximum ecological impact magnitude of ‘major’ (negatively affecting ecological community composition). **Medium-priority species** were those with a maximum ecological impact magnitude of ‘moderate’ (negatively affecting a native species’ population). **Low-priority species** were those with a maximum ecological impact magnitude of ‘minor’ or ‘minimal concern’. We classified a species as **Data Deficient** when there were zero published scientific papers about their impacts. In order to identify commonalities across species, we summarized all species based on the most common impact mechanisms, affected taxa, and impact scores.

The EICAT protocol includes a report of confidence in the impact score (high, medium, low; Hawkins et al. 2015). However, because confidence scores are defined somewhat subjectively (e.g., were data reported at an appropriate spatial scale?, was the data quality good?), we were not confident that our interpretation of confidence would be consistent with other scorers and therefore elected to exclude a confidence score. Instead, we performed a second evaluation of all high-priority species to ensure that these species were a high risk for ecosystems in New York and southern New England. We assessed whether each high-priority species was the likely driver of major impacts reported in the papers (Table S2), whether the species was absent from the Northeast region and therefore a candidate for EDRR, and whether impacts were reported in habitats similar to those found in Northeast ecosystems.

Results

To evaluate impacts for the 100 range-shifting invasive plants, we scanned titles and abstracts of 14,263 papers and compiled data from 865 impacts studies. A total of 82 species were given a prioritization: 20 species were identified as high-priority, 36 species medium-priority, and 26 species low-priority (**Table 1**). For the prioritized species, the average number of impact papers per species was 10.1 (±1.5 SE; range 1-71). High-priority species tended to have more papers, with an average of 15.4 (±3.8 SE; range 1-58) studies while low-priority species had fewer papers (average 4.4 ±1.1 SE; range 1-18). The remaining 18 species were data deficient (**Table S3**). Of the 20 high-priority species, two had unresolved taxonomies that made it unclear if impacts papers were associated with that species (*C. chalepensis, R. vestitus*) and three had reported ecological impacts that were anecdotal or correlational with low confidence in causality (*C. lanatus, C. lanceolata, T. hirtum*). The remaining 15 species have 'major' negative impacts on ecological communities. Of these, two were already present throughout the region based on USDA plants and therefore not candidates for eradication or prevention (*E. esula, S. pratensis*). Eight species had major negative impacts, but in habitats that are not currently found in the Northeast U.S. (*A. elliptica, C. selloana, E. erecta, H. altissima, P. pinaster, T. aphylla, T. chinensis, V. dubia*). Thus, five species were ultimately considered high priority for proactive management because they have major ecological impacts on habitat types that are also found in the Northeast U.S. and because they are not yet widespread in the region: *A. caucalis* and *A. donax* are present in nearby mid-Atlantic states, *A. barbata* is reported in Massachusetts, but not neighboring states, *L. grandiflora* is reported in New York, but not neighboring states, and *R. ulmifolius* is present in nearby mid-Atlantic states. **Table S4** outlines the habitats associated with the 15 'major' impact species.

Table 1. Final assessments of impact mechanisms and maximum reported impact magnitude (1-4) for each impact mechanism for the 82 ranked species. Ranks are High (H), Medium (M), or Low (L) priority. Impact mechanisms are as follows: BF = Bio-Fouling; CH = Chemical Impact; CO = Competition; DT = Disease Transmission; HY = Hybridization; IN = Interaction with Alien Taxa; PH = Physical Impact; PT = Poisoning/Toxicity; ST = Structural Impact; AG = Agricultural Impact; EC = Economic Impact; HH = Human Health Impact. Agricultural, Economic, and Human Health impacts are shown as Present (P). No Data is shown as (-). Current estab. refers to whether the species could establish in the region under current and future (Y) or only future (N) climate conditions. Underlined species are already present in one or more of the target states according to USDA Plants.

Name (Genus species)	Rank	BF	CH	CO	DT	HY	IN	PH	PT	ST	AG	EC	HH	Current Estab.	No. Papers
High-Priority Species – Major Ecological Impact															
Anthriscus caucalis	H	**4**	-	-	-	-	-	-	-	-	-	-	-	Y	3
Ardisia elliptica	H	**4**	-	-	-	-	-	-	1	-	-	-	-	N	3
Arundo donax	H	-	3	**4**	-	-	3	**4**	**4**	-	P	-	-	N	22
Avena barbata	H	-	1	**4**	-	3	1	2	**4**	-	P	-	P	N	27
Cardaria chalepensis	H	-	-	**4**	-	-	-	3	-	-	P	-	-	Y	2
Carthamus lanatus	H	-	-	**4**	-	-	-	-	3	-	P	-	-	N	3
Cortaderia selloana	H	-	3	**4**	-	-	-	**4**	2	-	P	-	-	N	16
Cunninghamia lanceolata	H	-	3	**4**	-	-	-	3	3	-	-	-	P	Y	58
Ehrharta erecta	H	-	3	**4**	-	-	3	-	-	-	-	-	-	N	2
Euphorbia esula	H	3	2	**4**	-	-	**4**	**4**	2	3	P	P	P	Y	54
Hemarthria altissima	H	-	-	**4**	-	-	-	-	3	-	P	-	-	N	5
Ludwigia grandiflora	H	**4**	-	**4**	-	-	3	3	**4**	**4**	P	P	P	Y	11
Pinus pinaster	H	-	1	**4**	-	-	-	**4**	-	-	P	P	-	Y	10
Rubus ulmifolius	H	-	2	**4**	-	3	2	3	2	3	P	-	-	Y	20
Rubus vestitus	H	-	-	**4**	-	2	-	3	-	3	-	-	-	Y	1

Schedonorus pratensis	H	-	-	**4**	-	-	-	-	**4**	-	P	-	-	Y	13
Tamarix aphylla	H	-	**4**	**4**	-	-	-	**4**	**4**	**4**	-	-	-	N	8
Tamarix chinensis	H	-	3	**4**	-	3	2	**4**	**4**	**4**	-	-	-	N	30
Trifolium hirtum	H	-	-	**4**	-	-	-	-	-	-	P	-	-	Y	4
Ventenata dubia	H	-	-	**4**	2	-	-	-	-	3	-	-	-	Y	4
Medium-Priority Species – Moderate Ecological Impact															
Achyranthes japonica	M	-	-	1	-	-	-	-	-	3	P	-	-	Y	3
Alyssum murale	M	-	2	3	-	-	1	-	2	-	-	-	-	Y	4
Araujia sericifera	M	-	-	-	-	-	3	-	-	2	P	-	P	N	3
Asclepias curassavica	M	-	-	-	3	2	1	-	3	3	P	-	P	N	14
Bellardia trixago	M	-	-	-	-	-	-	-	3	-	-	-	-	N	1
Brachypodium distachyon	M	-	2	-	3	-	-	3	-	-	P	-	P	N	71
Cardaria pubescens	M	-	-	-	-	-	-	3	-	-	P	-	-	Y	2
Centranthus ruber	M	-	-	3	-	-	-	-	-	-	P	-	-	Y	2
Cestrum diurnum	M	-	-	-	-	-	2	-	3	-	P	-	-	N	5
Ceratocephala testiculata	M	-	-	3	-	-	-	-	-	-	-	-	-	Y	1
Conyza bonariensis	M	-	-	-	-	-	-	-	3	3	P	-	-	N	15
Cytisus striatus	M	-	1	3	-	-	1	-	-	-	-	-	-	Y	4
Dalbergia sissoo	M	-	2	3	-	-	-	-	2	-	P	-	P	N	16
Daphne laureola	M	-	-	3	-	-	-	-	-	-	-	-	-	Y	2
Festuca brevipila	M	-	-	3	-	-	-	-	1	-	-	P	-	Y	3
Hedera helix ssp. canariensis	M	-	2	-	3	-	-	-	3	3	P	P	-	N	7

Hedera hibernica	M	-	-	3	-	-	-	-	-	-	-	-	-	Y	2
Hypericum calycinum	M	-	-	2	2	-	-	-	3	-	-	-	-	Y	3
Lagerstroemia indica	M	-	-	1	3	2	2	-	-	3	-	-	-	N	15
Ligustrum japonicum	M	-	-	-	3	-	-	1	-	2	-	-	-	N	9
Lotus pedunculatus	M	-	2	3	-	1	2	-	2	-	P	-	-	Y	26
Lythrum virgatum	M	-	-	-	-	3	-	-	3	-	-	-	-	Y	2
Mahonia bealei	M	-	-	3	-	-	-	-	-	-	-	-	-	Y	1
Nandina domestica	M	-	-	2	3	-	-	-	-	-	-	-	-	N	3
Oplismenus hirtellus	M	-	-	-	-	-	3	-	-	-	-	-	-	Y	1
Paspalum urvillei	M	-	-	-	3	-	3	-	-	-	-	-	-	N	5
Peganum harmala	M	-	1	2	-	-	-	-	3	-	P	-	P	N	19
Persea americana	M	-	2	3	-	-	3	2	-	3	P	-	P	N	34
Prunus laurocerasus	M	-	2	3	2	1	-	2	-	-	P	-	-	Y	12
Quercus acutissima	M	-	3	2	2	-	2	2	-	-	-	-	-	Y	11
Senna occidentalis	M	-	-	-	-	-	3	-	3	-	P	-	P	N	34
Sesbania punicea	M	-	-	-	-	-	3	-	3	1	-	-	-	N	4
Sinapis arvensis	M	-	3	-	-	3	-	-	-	-	P	-	P	Y	12
Spartium junceum	M	-	2	3	-	-	2	3	3	-	P	-	P	Y	11
Stellaria media	M	-	2	3	-	-	-	-	-	-	P	P	P	Y	47
Tamarix africana	M	-	-	3	-	-	-	-	-	-	-	-	-	Y	1
Low-Priority Species – Minor or Minimal Ecological Impact															
Aegilops ovata	L	-	-	-	-	2	-	-	2	-	P	-	-	Y	17
Alhagi maurorum	L	-	-	-	-	-	2	-	2	-	P	-	-	Y	5

Anchusa arvensis	L	-	-	-	-	-	-	-	2	-	P	-	-	Y	2
Arum italicum	L	-	-	-	-	2	2	-	1	-	-	-	-	Y	3
Avena sterilis	L	-	-	-	-	2	-	-	-	-	P	-	-	Y	18
Buddleja lindleyana	L	-	-	-	-	1	-	-	-	-	-	-	-	N	2
Carduus tenuiflorus	L	-	-	-	-	-	-	-	-	1	-	-	-	N	1
Centaurea iberica	L	-	-	-	-	-	-	-	-	-	P	-	P	Y	1
Centaurea melitensis	L	-	2	2	-	-	-	-	-	-	-	-	-	Y	2
Centaurea virgata	L	-	-	-	-	-	1	-	-	-	-	-	-	Y	1
Crotalaria spectabilis	L	-	1	-	-	-	2	-	-	-	P	-	-	N	17
Elaeagnus pungens	L	-	1	-	-	-	-	-	-	-	-	-	-	Y	1
Firmiana simplex	L	-	-	-	1	-	1	-	-	-	-	-	-	N	2
Hibiscus tiliaceus	L	-	-	-	-	-	2	-	-	2	P	-	-	N	6
Leontodon taraxacoides	L	-	-	-	-	-	-	-	-	-	P	-	-	Y	1
Phyllostachys aurea	L	-	-	-	-	-	2	-	-	-	P	P	-	N	3
Poncirus trifoliata	L	-	-	2	-	-	-	-	-	-	P	-	-	Y	4
Prunus lusitanica	L	-	-	-	-	-	2	-	-	-	-	-	-	N	1
Pseudognaphalium luteoalbum	L	-	-	2	-	-	-	-	2	-	-	-	-	Y	2
Rumex stenophyllus	L	-	-	-	-	-	-	-	-	1	-	-	-	Y	1
Sacciolepis indica	L	-	-	1	-	-	-	-	-	-	-	-	-	Y	1
Stachys arvensis	L	-	-	-	-	-	1	-	-	-	P	-	-	Y	4

Tripleurospermum perforatum	L	-	-	-	-	-	-	-	-	-	P	-	-	Y	1
Vitex agnus-castus	L	-	2	2	-	-	-	-	2	-	P	-	P	Y	17
Vitis vinifera	L	-	-	1	-	2	2	-	-	-	P	-	-	Y	11
Youngia japonica	L	-	-	-	-	-	-	-	-	-	P	P	-	Y	3

The most frequent ecological impact mechanisms were competition, poisoning/toxicity, and interaction with other alien species, while biofouling, disease transmission, and hybridization were the least commonly reported (**Figure 1A**). Although biofouling impacts were rarely reported, they were proportionally most likely to cause major impacts on communities. Competitive and physical impacts were also more likely to have ‘major’ negative impacts on ecological communities. Therefore, data-deficient species (**Table S3**) known to cause biofouling, be strong competitors, or alter the physical characteristics of an ecosystem might be higher risk.

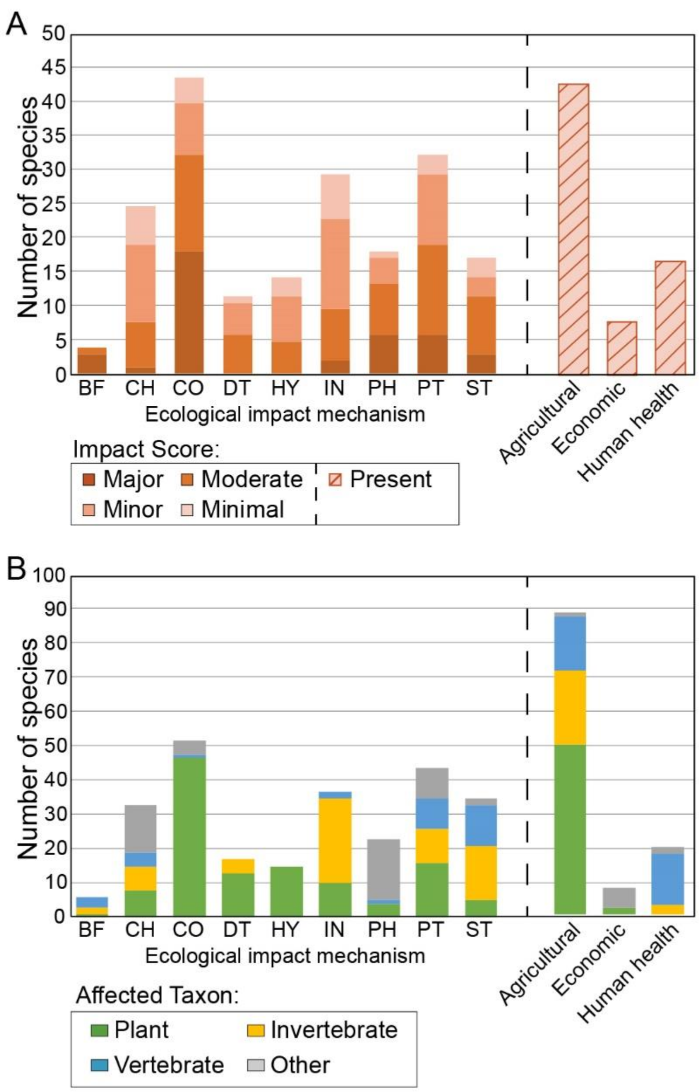

Figure 1. Magnitude of impact and affected taxa for the 82 ranked invasive plants. Ecological impact mechanisms are as follows: BF = Bio-Fouling; CH = Chemical Impact; CO = Competition; DT = Disease Transmission; HY = Hybridization; IN = Interaction with Alien Taxa; PH = Physical Impact; PT = Poisoning/Toxicity; ST = Structural Impact. A) Maximum impact scores for the 82 species associated with each ecological impact mechanism or socio-economic system. Major ecological impacts were most common through biofouling, competition, physical impacts on the ecosystems, and poisoning/toxicity (allelopathy). Impacts to agriculture, economics, and human health were marked as present, but not scored. B) Affected taxa for the 82 species associated with each ecological impact mechanism or socio-economic system. Plants and invertebrates were most commonly affected by the 82 invasive plants, but vertebrates in ecosystems and agricultural systems were also affected through poisoning/toxicity. 'Other' taxa are typically studies with no reported impact on species (e.g. altered structure or chemistry of an ecosystem), but also include impacts on fungi.

Of the socioeconomic impacts, Agriculture was the most common affected system (**Figure 1A**), occurring in 45 of 82 prioritized species (55%), followed by Human Health (17 species; 21%) and Economic (8 species; 10%). Transmission of diseases to crops (26 of the 45 species with agricultural impacts; 58%) was one of the most frequently reported agricultural impact. Competition with crops and forage grasses (which reduced crop yield and pastureland carrying capacity) was reported in 19 of the 45 species (42%). Interaction with other invasive species, typically involved facilitation of invasive insect pests, was also reported as an agricultural impact mechanism in 17 of the 45 species with agricultural impacts (38%). Lastly, toxic effects on livestock, which cause weight loss, avoidance, or even fatal poisoning, was reported in 16 of the 45 species (36%).

Invasive plants most commonly affected native plants or plant communities and invertebrate animals (**Figure 1B**). Competition, disease transmission, and hybridization were proportionally most likely to affect native plants. Animals were most likely to be affected through interactions (e.g., facilitation of a non-native animal that preys upon or competes with a native animal), structural changes (e.g., reduced habitat), and poisoning/toxicity (e.g., toxic to native animals). Allelopathy, recorded as poisoning/toxicity, was also likely to affect belowground arbuscular mycorrhizal fungi (other in **Figure 1B**). 'Other' affected taxa were also likely in cases where impacts were not tied to a specific ecological response, which was most common for chemical impacts (e.g., changes in carbon storage) and physical impacts (e.g., increased fire frequency or altered stream hydrology). Vertebrate animals affected by invasive plants in agriculture were typically livestock; invertebrate animals were typically crop pests facilitated by invasive plants.

Discussion

The Northeast U.S. has been identified as a hotspot for future invasion risk under climate change (Allen and Bradley 2016). Up to 100 invasive plant species are projected to expand into the region, threatening native ecosystems, agricultural systems, and economies. Because the identity of these range-shifting species is known (Allen and Bradley 2017), there is currently a unique opportunity to prevent the introduction and spread of high-impact species into this increasingly vulnerable region. The large number of range-shifting invasive plants coupled with limited resources makes early detection and rapid response of all 100 species a challenge, thus, prioritizing range-shifting invasive plants is a critical step to inform effective prevention strategies. Getting a step ahead of the expected invasions by targeting high-impact species will not only allow us to use resources most effectively, but also increase the likelihood of success (Mack et al. 2000; Rejmánek and Pitcairn 2002).

This study illustrates how the combination of watch lists and impacts assessments can provide an effective tool for proactive management of invasive plants in the context of climate change. From a list of 100 species, we identified five as high priority due to reported impacts in ecological communities and invading ecosystems similar to those found in New York and southern New England. Aside from reported impacts, these five species are highly likely to invade the Northeast due to recent establishment in this region and/or known introduction pathways that could lead to rapid establishment and spread. For example, the invasive species *Ludwigia grandiflora* (large-flower primrose-willow), which has already been reported in New York, creates anoxic conditions in freshwater systems which could easily damage vulnerable aquatic flora and fauna (Dandelot et al. 2005). Another high-priority species with the potential to establish by mid-century is *Arundo donax* (giant cane). *A. donax* has been promoted as a biofuel

(Corno et al. 2014) despite well-documented negative impacts on riparian ecosystems (Mack 2008) and agriculture (Racelis et al. 2012). Of the five high-priority species, three (*A. donax, L. grandiflora*, and *R. ulmifolius*) have a history of deliberate introduction either as ornamentals or for biofuels. The remaining high-priority species (*A. caucalis* and *A. barbata*) were likely introduced accidentally as crop contaminants. Knowing the identity and introduction pathways of high-priority species creates an opportunity to stop future introductions and proactively remediate future impacts.

Policy and Management

The likelihood that new, high-impact invasive plants will soon emerge in the Northeast U.S. highlights the need for proactive policies to prevent their introduction. Most states have some sort of regulated plants list, which restricts or prohibits the sale of known invasive plants. However, most regulated plants are ones already established and invasive in the state, making these regulations reactive rather than proactive. Moreover, the listing procedures make it challenging to proactively list species likely to shift into the Northeast with climate change. For example, the ranking system for invasive plants in New York state includes criteria about climate matching, where the maximum score is associated with species whose "native range includes climates similar to those in New York" (New York Invasive Species Council 2010). Similarly, invasive plant evaluations conducted by the Massachusetts Invasive Plant Advisory Group include the criterion that the species have a "documented history of invasiveness in other areas of the northeast" (Massachusetts Invasive Plant Advisory Group 2005). In both cases, range-shifting invasive plants will not meet these criteria because the current climate of New York does not match their native range and they are not yet invasive in the Northeast. Thus, current regulatory frameworks for identifying and preventing the introduction of invasive plants need to be adapted to encompass the reality of range-shifting due to climate change.

In addition to the need for proactive regulation, better coordination of invasive plant lists is needed between Northeast states. Given that three of the five high-priority species have been introduced deliberately to the U.S. as ornamentals or biofuels, the introduction of these species to the Northeast once climate conditions are suitable is a distinct possibility. Currently, every state has a different protocol for evaluating invasiveness – often drawing from expert knowledge, which can lack transparency. In contrast, EICAT is a useful method for prioritization because it is repeatable, transparent, and provides an estimate of the magnitude of impact. All of the 865 papers we assessed are reported in the resulting database, so users can easily find these sources and evaluate species based on their specific management concerns. Moving towards a single, repeatable approach for evaluating potential impacts could lead to greater consistency in state regulated lists and a united defense against future invaders.

Evaluating the magnitude of potential impact in a repeatable fashion is critical for prioritization, particularly given the need to coordinate watch lists across state jurisdictional borders in the Northeast. Currently, weed risk assessment protocols vary considerably in terms of how impacts are evaluated. For example, the Australian Weeds Risk Assessment (Pheloung et al. 1999) included nine factors related to potential impact, which are answered on a yes/no basis. In contrast, Koop et al. (2012) recommended 16 impact categories, while Conser et al. (2015) recommended four and Booy et al. (2017) included only overall impact. Of these, only Booy et al. (2017) recommended an estimate of magnitude of impact (following the EICAT categories used here). Yes/no scoring of impact fails to differentiate between magnitude of potential impacts, which is critical for prioritization. Thus, EICAT, which evaluates magnitude of impact, is an appropriate approach to consistently and transparently rank potential impacts and identify high-impact species. Moving beyond impact assessment and prioritization, managers' highest priority research on invasive species and climate change is identifying ecosystems vulnerable to future invasion (Beaury et al. 2019). While we considered invaded habitats when refining our high-priority list for the Northeast U.S., more work is needed to identify likely areas of initial introduction and spread (e.g., Padayachee et al. 2019) in order to inform monitoring for EDRR. Additionally, best management practices (BMPs) have not been developed for these species for Northeast U.S. ecosystems. In order to develop and refine BMPs for their region, invasive species managers will need to reach out to partners much further afield than they might be currently accustomed. For example, *R. ulmifolius* currently has reported populations in Maryland, which are several hundred kilometers from the New York border. Given the potential for these species to be introduced deliberately once the climate is right, the development of BMPs would benefit from broader networks of invasive species managers (e.g., Barney et al. 2019).

Impact Mechanisms

There was a clear trend in the mechanisms of invasive plant impact, with the target species predominantly impacting recipient ecosystems via competition, poisoning/toxicity, and interaction with other invasive species (**Figure 1A**). Additionally, invasive plants frequently have detrimental impacts on agricultural systems, which was the most commonly reported socio-economic impact. While the majority of impacts were reported on native plant communities or plant crops (**Figure 1B**), several studies also reported impacts cascading up to higher trophic levels. For example, *Achyranthes japonica* (Japanese chaff flower) reduces breeding carrying capacity for the seabird, Swinhoe's storm petrel, by invading native grasslands and reducing potential nesting sites (Arcilla et al. 2015). This evidence is consistent with a recent meta-analysis showing that terrestrial invasive plants tend to have negative impacts on native insects and other higher trophic levels (Bradley et al. 2019).

Data limitations

These results suggest that invasive plant impacts are fairly well-studied, but additional research is needed for species with low numbers of impact papers, especially data-deficient species. We found at least one impact paper for 82% of the evaluated species. In contrast, Evans et al. (2016) compiled reports of environmental impacts for 30% of 415 invasive birds and Kumschick et al. (2017) found sufficient information for 38% of 105 invasive amphibians. In a study of bamboo, Canavan et al. (2019) found impacts information for only 15% of 135 naturalized bamboo species. However, this low percentage might be due to the focus on naturalized species rather than the subset of invasive species. Based on our results, plants identified as invasive are likely to have some form of reported impacts.

Although 60 species were classified here as low- or medium-priority, the lack of reported impacts on native communities should not be interpreted as evidence of an absence of impact. Many impact studies do not set out to measure community-level impacts (Bradley et al. 2019). Thus, these species should remain under consideration for future prioritization, particularly those with few or no impact papers.

Finally, the range-shifting invasive plants evaluated here only encompass species that are already present and recognized as invasive somewhere within the U.S. (Allen and Bradley 2016). Non-native plants continue to be introduced at increasing rates (Seebens et al. 2017) both accidentally (most often as seed contaminants; Lehan et al. 2013) and deliberately (most often as ornamentals; Reichard and White 2001; Mack and Erneberg 2002; Lehan et al. 2013) and a large proportion of these introduced species may go on to become invasive (Jeschke and Pysek 2018). Moreover, there is evidence that many introduced species are 'pre-adapted' to warmer climate conditions associated with climate change (Bradley et al. 2012; Seebens et al. 2015), which could increase future rates of invasion. Thus, while a focus on range-shifting invasive species is an important piece of proactive management, a continued focus on new imports is also needed.

Conclusions

EICAT is a repeatable and transparent protocol that can be used to prioritize invasive plants likely to shift their ranges with climate change. Our analysis narrowed a large set of 100 species down to a manageable target of five high-priority species. Therefore, impacts assessments can serve as a valuable tool for targeting harmful species for early detection and rapid response, increasing the likelihood of successful prevention of future invasions. This type of consistent risk assessment approach inclusive of climate change is needed in order to develop proactive regulation and management across multiple jurisdictional borders.

Data availability: Data are permanently archived through UMass Scholarworks.
Appendix 1. Database of impact assessments https://doi.org/10.7275/jt7g-zv93
Appendix 2. Summary reports for individual species https://doi.org/10.7275/yygq-0r05

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